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Comparison of H II region luminosities with observed stellar ionizing sources in the Large Magellanic Cloud

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ABSTRACT

We estimate the total predicted Lyc emission rates of OB associations for which the complete census of O star spectral types exists. The results are compared to the observed Hα luminosities of the host H II regions. We find evidence for substantial leakage of ionizing photons from some H II regions, while others appear to be radiation bounded. We estimate that overall for the LMC, 0–51% of the ionizing radiation escapes the local nebulae, and would be available to ionize the diffuse, warm, ionized medium (WIM) in that galaxy. This range of values is consistent with the observed 35% fraction of Hα luminosity emitted by the WIM in the LMC, as well as the corresponding fractions observed in other nearby galaxies. It is therefore possible that photoionization by O stars is indeed the dominant ionization mechanism for the WIM.

Key words: stars: early-type – ISM: general – H II regions – Magellanic Clouds

1 INTRODUCTION

The balance of evidence currently suggests that the ionization of the diffuse, warm, ionized component of the interstellar medium (ISM) is caused primarily by O stars. From an energetic standpoint, this stellar population has long been targeted as one of the only sources capable of generating the large power requirement (e.g., Reynolds 1984) of this warm, ionized medium (WIM). Models of the WIM that assume ionization by O stars are broadly consistent with its observed properties in the Galaxy (Miller & Cox 1993; Dove & Shull 1994), and confirm that O stars are more than capable of providing the necessary ionizing power. In fact, these studies suggest that an excess of ionizing luminosity is produced, implying the escape of that radiation from the Galaxy. Observations of the WIM in nearby, external galaxies show concentrations of the diffuse gas near conventional H II regions, further suggesting the association of the WIM with O stars (Walterbos & Braun 1994; Ferguson et al. 1996).

However, there are notable complications to the O star ionization hypothesis. Perhaps most problematic is the observed limit to the ratio of the recombination lines He I λ5876 / Hα, implying relative ionizing photon emission rates for He vs. H of $Q(\mathrm{He}^0)/Q(\mathrm{H}^0) \lesssim 0.03$ (Reynolds & Tufte 1995; Heiles et al. 1996). The implied ionizing spectrum in the Galaxy therefore appears to be much softer than anticipated from the O star population, implying an unusually low effective upper-mass cutoff to the stellar initial mass function (IMF) of $\lesssim 30\,\mathcal{M}_\odot$, and forcing an unrealistically large Galactic star formation rate (Heiles et al. 1996). Rand (1997) presents a deep spectrum of the WIM in the edge-on galaxy NGC 891, finding $Q(\mathrm{He}^0)/Q(\mathrm{H}^0) \sim 0.08$, which is much more consistent with hot star ionization. Measurements of the He and H recombination lines in the WIM of three dwarf irregular galaxies by Martin & Kennicutt (1997) are also consistent with He being mostly ionized in those objects, as expected from phoionization of stars with a normal IMF. However, NGC 891 exhibits an anomalously high ratio of [N II]λ6583/Hα $\sim 1 - 1.4$, again implying an even harder ionizing spectrum than indicated by Rand's He I/Hα ratio. There is also some doubt about the ability of the stellar ionizing radiation to travel the required hundreds of parsecs, although models by Dove & Shull (1994) and Miller & Cox (1993) show tentative compatibility. Investigations of the superbubble structure of the ISM (Heiles 1990; Rosen & Bregman 1995; Oey & Clarke 1997) also suggest the widespread existence of large voids, which would facilitate radiative transfer over such large distances. Finally, alternative or additional ionizing sources are likely to play a role in the WIM as well. These include turbulent mixing layers (Slavin, Shull, & Begelman 1993), neutrino decay from dark matter (Sciama 1990, 1995), white dwarfs, cosmic rays (Liu & Dalgarno 1997), and extragalactic ionizing radiation (e.g., Reynolds et al. 1995).

In general, however, O stars remain as the most likely dominant source of ionization for the WIM. But is the sim-

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Table 1. Sample of OB / H II Systems

LH	DEM	Henize	Reference
2	10B	N79 CE	J. Wm. Parker, unpublished
...	25	N185	Oey (1996a)
6	31	N9	Oey (1996a)
9, 10	34	N11	Parker et al. (1991)
...	50	N186	Oey (1996a)
38	106	N30 BC	Oey (1996a)
47, 48	152, 156[a]	N44	Oey & Massey (1995)
51, 54	192	N51 D	Oey, in preparation
58	199	N144	Garmany et al. (1994)
73	226	N148 I	Oey (1996a)
83	243	N63 A	Oey (1996a)
110	293	N214 C	Conti et al. (1986)
114	301	N70	Oey (1996a)
117, 118	323, 326	N180	Massey et al. (1989)

[a]Not including DEM 152A.

ple, empirical comparison of available ionizing photons vs. ionized gas actually consistent with this scenario? Abbott (1982) predicts that roughly 15% of the available ionizing flux of O stars in the solar neighborhood is required to ionize the local WIM, a result supported by Dove & Shull (1994) and Miller & Cox (1993). This therefore implies that, if the large-scale WIM is similar to that in the solar neighborhood, at least $\sim 15\%$ of the OB Lyman continuum (Lyc) flux must escape the H II regions. Photoionization models of the WIM by Domgörgen & Mathis (1994) further suggest that 4% of the total flux must escape the Galaxy altogether, in which case a certain fraction of the ionized regions must be density-bounded. However, historically, most H II regions have been considered to be essentially radiation-bounded, rather than density-bounded, allowing the nebular luminosities to be used quite successfully as tracers of massive star formation. It is therefore worth examining more closely the comparison of available Lyc and nebular fluxes.

We can investigate this effect with a sample of OB associations whose stellar populations have been classified, and whose host nebulae have measured total luminosities. The Large Magellanic Cloud (LMC) provides an ideal sample, with detailed studies of over a dozen OB associations (e.g., Massey et al. 1995b; Oey 1996a), and a uniform catalog of nebular photometry (Kennicutt & Hodge 1986) at low extinction. We now use this sample of OB/H II systems to examine the fraction of Lyc radiation escaping from the H II regions, as indicated by the currently available stellar atmosphere models.

2 METHODS

Table 1 lists the sample of OB associations, designated by their Lucke & Hodge (1970) identification; and host nebulae, given by their Davies, Elliott, & Meaburn (1976), and Henize (1956) identifications. The OB associations all have available spectroscopic classifications for the hottest stars. These classifications are essential in constraining the Lyc fluxes of the stars, since the spectral types cannot be reliably distinguished from broad-band colors alone (e.g., Massey 1985). The reference for the spectral types is given in the fourth column of Table 1.

To compare the predicted stellar ionizing flux with the H II region luminosity, we summed the Lyc photon emission rates $Q(\mathrm{H}^0)$ for the individual stars, that have been estimated for the range of O star spectral types. Although this has already been carried out for several of the nebulae in this sample, we now redo these comparisons with more recent information and uniformly for the entire sample. At present, the values of $Q(\mathrm{H}^0)$ are rather uncertain, as discussed below. We therefore compute results using the tabulation by Panagia (1973, hereafter P73), Vacca, Garmany, & Shull (1996, hereafter VGS), and Schaerer & de Koter (1997, hereafter SdK). We then computed the resulting Hα luminosity implied by the total $Q(\mathrm{H}^0)$ of each OB association, assuming an electron temperature $T_e = 10,000$K. We reconfirmed the Lyc/Hα photon conversion of 2.2 for $T_e = 10,000$K from the results of Hummer & Storey (1987). The stellar studies also provide extinction data with which we arrive at a final estimate for the predicted H II region luminosity, using $A_{\mathrm{H}\alpha} = 2.5\ E(B-V)$ (e.g., Parker et al. 1992). The adopted $E(B-V)$ are median color excesses, with the exception of values for DEM 34, DEM 199, and DEM 323/326, which are mean values. The adoption of the median or mean is taken directly from the cited reference; differences in the respective characterization of $E(B-V)$ have negligible effect in this analysis. Table 2 lists the nebular identification in column 1, and in columns 3 – 5, the extinction-corrected Hα luminosities predicted from the spectral type – Lyc flux conversions of P73 (L_{P}), VGS (L_{VGS}), and SdK (L_{SdK}). Column 6 shows the total $Q(\mathrm{H}^0)$ for the classified O stars, using the SdK conversion; the different conversions and choice among these are discussed in §3 below. The number of classified O stars ($n_\star$) and $B-V$ color excess are given in columns 7 and 8.

The Hα luminosities of the H II regions were measured using the photographic photometry of Kennicutt & Hodge (1986, hereafter KH86). Details of the observations and data can be found in the original paper. The plates used in KH86 were rescanned at higher angular resolution and recalibrated using sensitometer exposures obtained during the observations, photoelectric photometry from KH86 and Caplan & Deharveng (1986), and CCD images of 30 Doradus obtained by RCK with the CTIO 1.5m telescope and Rutgers Fabry-Perot camera. This produced a series of Hα surface brightness maps corresponding to each of the four photographic fields covering the LMC. Integrated fluxes for each H II region were measured, using the stellar data to ensure that the nebular regions measured conformed as closely as possible to the regions ionized by the OB associations of interest. The boundaries of the H II regions are well-defined in most instances, so the determination of the apertures for the Hα flux measurements was unambiguous. No corrections for extinction were applied to these data, since extinction is taken into account for the predicted Hα luminosities in Table 2. The fluxes we derive show excellent agreement with the measurements of Caplan & Deharveng (1986) for objects in common (see below). The observed Hα luminosities L_{obs} of the H II regions in our sample are given in column 2 of Table 2.

The last column of Table 2 shows the ratio of observed to predicted Hα luminosity, $L_{\mathrm{obs}}/L_{\mathrm{SdK}}$. If $Q(\mathrm{H}^0)$ is a reasonable estimate of the true ionizing photon emission, then we can use $L_{\mathrm{obs}}/L_{\mathrm{SdK}}$ to obtain the fraction of ionizing radiation escaping from the H II region. For DEM 25 and DEM 50, these values are $\gg 1$. Interestingly, the morphology of

Table 2. Observed and Predicted H II Region Luminosities

H II Region	$L_{\rm obs}$ (erg s^{-1})	$L_{\rm P}$ (erg s^{-1})	$L_{\rm VGS}$ (erg s^{-1})	$L_{\rm SdK}$ (erg s^{-1})	$Q(\rm H^0)$ (s^{-1})	$n_\star$	$E(B-V)$ (mag)	$L_{\rm obs}/L_{\rm SdK}$
DEM 10B	6.68E+37	5.33E+37	9.61E+37	8.24E+37	8.64E+49	7	0.16	0.81
DEM 25	2.64E+37	2.23E+36	3.88E+36	3.08E+36	2.88E+48	1	0.11	8.57
DEM 31	6.42E+37	1.11E+38	1.73E+38	1.62E+38	1.45E+50	6	0.09	0.40
DEM 34	5.46E+38	6.83E+38	9.37E+38	8.33E+38	7.61E+50	44*	0.10	0.66
DEM 50	4.61E+37	1.61E+37	2.70E+37	2.30E+37	2.20E+49	3	0.12	2.00
DEM 106	3.43E+37	4.15E+37	7.34E+37	5.55E+37	5.56E+49	8	0.14	0.61
DEM 152+156[a]	2.32E+38	3.18E+38	4.11E+38	3.52E+38	3.22E+50	35*	0.10	0.66
DEM 192	2.50E+38	2.61E+38	3.66E+38	3.03E+38	2.71E+50	25*	0.09	0.83
DEM 199	4.09E+38	3.00E+38	3.94E+38	3.34E+38	2.72E+50	22*	0.05	1.22
DEM 226	2.23E+37	1.65E+37	2.85E+37	2.41E+37	2.53E+49	4	0.16	0.93
DEM 243	5.22E+37	6.14E+37	1.19E+38	9.72E+37	8.88E+49	11	0.10	0.54
DEM 293	4.97E+37	8.11E+37	4.78E+37	4.56E+37	4.79E+49	1	0.16	1.09
DEM 301	4.84E+37	1.87E+38	2.65E+38	2.45E+38	2.04E+50	7	0.06	0.20
DEM 323+326	3.30E+38	3.88E+38	3.24E+38	2.92E+38	2.80E+50	20	0.12	1.13

*WR star excluded; DEM 199 contains 3 WR stars.
[a]Not including DEM 152A.

these two nebulae is similar. Both objects are shells that show evidence of recent supernova activity (Oey 1996b), although their $L_{\rm obs} \sim 10^{37}$ erg s^{-1} is one to two orders of magnitude brighter than typical supernova remnants (SNRs). However, simulations of supernova impacts on pre-existing shells show that peak Hα luminosities of $\sim 10^{37}$ erg s^{-1} might be achieved for a short flash in time (Tenorio-Tagle et al. 1990). It therefore seems possible that there may be a dominant contribution from shock ionization in DEM 25, where the photometry suggests that identification of the O stars is complete (Oey 1996a). DEM 50 has a confirmed SNR at the north end of the main shell, and it is difficult to determine its contribution to the total Hα luminosity. However, photometry for this region (Oey 1996a) indicates that significant O stars may remain unclassified for DEM 50 in comparison to the other nebulae in the sample. For these reasons, we will not consider DEM 25 and DEM 50 any further in the comparison of Lyc emission to Hα luminosity. We also caution that DEM 243 contains an SNR as well, but given the ratio of $L_{\rm obs}/L_{\rm SdK}$, it is apparent that the SNR does not contribute significantly to the Hα luminosity.

3 UNCERTAINTIES

The median of the ratio $L_{\rm obs}/L_{\rm SdK}$, the observed to predicted Hα luminosity, is 0.74, excluding DEM 25 and 50. Because of the possibility of unidentified stars and other effects yielding an asymmetric distribution, the median is the preferred measurement of a characteristic value, although we note that the mean value is 0.76, in close agreement with the median. There are large uncertainties in the median estimate, stemming from many factors. We adopt a distance modulus to the LMC of 18.5 (e.g., Panagia et al. 1991), with an error of $\pm 10\%$. Our adopted nebular electron temperature $T_e = 10,000$K (e.g., Pagel et al. 1978), yielding an uncertainty in the ratio of Hα photons to Lyc photons of $\pm 1\%$. Additional important errors result from the effect of stars that are unaccounted for, uncertainties in modeled Lyc emission rates, and observational errors.

The number of classified O stars is a lower limit to the actual number present, and the values of $Q(\rm H^0)$ in Table 2 do not include contributions from B stars and Wolf-Rayet (WR) stars. All of the WR stars in these H II regions are WNE or WC types. DEM 34, DEM 152+156, and DEM 192 each contain one WR star, and DEM 199 contains 3 WR stars. DEM 31 contains a WN6 that falls in the spectral sequence of O3–4 If to WN-A stars (Oey 1996a), so we have attributed it the Lyc emission of an O3 I star. The ionizing fluxes of WR stars are quite uncertain, and, as shown by modeling of individual stellar atmospheres for WNL stars (Crowther & Smith 1997), they can vary enormously for individual spectral types. Given this caveat, model atmospheres suggest that WNE (Crowther & Smith 1996) and WC types may be expected to contribute roughly 10^{49} s^{-1} to the cluster ionizing emission (P. A. Crowther, private communication).

Early B stars may provide an additional significant source of ionization. *EUVE* observations of the B2 II star, ϵ CMa, revealed excess Lyc emission by a factor of 30 over model atmosphere predictions (Cassinelli et al. 1995). Subsequent observations of the B1 II-III star, β CMa, implied a possible excess of up to a factor of 5, although by adjusting the stellar effective temperature $T_{\rm eff}$, the observations could come into agreement with predictions (Cassinelli et al. 1996; SdK). It is therefore unclear to what degree ϵ CMa is an anomalous star, bearing in mind that it was selected for observation based in part on its bright EUV flux. It is also interesting that the observations of these two B stars suggest that the Lyc fluxes predicted by the models appear thus far to be lower limits. A discussion of effects and uncertainties in $Q(\rm H^0)$ estimates for early B stars may be found in SdK.

We also caution that predicted O star Lyc fluxes have not been observationally confirmed. As is apparent in Table 2, the predictions of $Q(\rm H^0)$ by P73 and VGS yield total ionizing luminosities that agree within a factor of 2 or less, while those of SdK are generally intermediate. The P73 values historically have been widely used, and are based on LTE line-blanketed models for cooler spectral types, and NLTE unblanketed models for hotter types. VGS presented a new set of $Q(\rm H^0)$ estimates based on updated stellar parameters and using LTE line-blanketed models. The factor

of $\lesssim 2$ difference between VGS and P73 is due primarily to the updated $T_{\rm eff}$ calibrations. Finally, the recent results by SdK should represent the best estimates of Lyc fluxes to date, since they account for NLTE, line-blanketing, and wind effects, within self-consistent models combining both stellar structure and atmospheres. More detailed comparison and discussion of relevant effects is carried out by VGS and SdK.

All these models assume solar metallicity ($Z_\odot$). SdK show that a decrease in metallicity is expected to increase $Q({\rm H}^0)$ slightly, owing to reduced line-blanketing. The degree of the increase is generally small, but a decrease from solar to $0.2Z_\odot$ could increase the Lyc output by up to 30% for individual spectral types, although these large effects apply primarily to the cooler types. However, an empirical spectral type – $T_{\rm eff}$ calibration has been lacking for low-metallicity stars, and if temperature effects are important, these could well dominate the Lyc output. In general, though, most arguments suggest that lower metallicity should tend to increase the stellar ionizing fluxes. At any rate, with LMC abundances around $0.4Z_\odot$, the increase in Lyc fluxes should be relatively small in light of the other uncertainties.

Our reddening estimates (Table 2) based on the stellar data are in good agreement with nebular extinctions measured by Caplan & Deharveng (1986) from the Balmer decrement. For the standard extinction assumptions described in their Appendix B, the mean difference in $E\,(B-V)$ between their estimates and ours is 0.01 mag for the 7 objects measured in common. The mean absolute value in the differences is 0.03 mag, suggesting an uncertainty of $\pm 7\%$.

The principal sources of error in the Hα measurements are spatial variations in response across the Curtis Schmidt plates, and the accuracy of the photographic density-intensity calibration, especially for low surface brightness regions as are found in some of the superbubbles. We estimate the typical uncertainties in the fluxes to be $\pm 10\%$ for the brighter regions, increasing to $\pm 15\%$ in the superbubbles, based on intercomparisons of objects observed on more than one plate, and from comparisons with the photoelectric measurements described above.

The uncertainties in the median value of $L_{\rm obs}/L_{\rm SdK} = 0.74$ that result from the factors mentioned above are strongly dominated by the large uncertainty in model atmosphere Lyc emission rates. This error is difficult to quantify, but we estimate that it is around 50%. We note that many effects such as those due to line-blanketing, wind-blanketing, and metallicity, tend to introduce uncertainties for cooler stars, whereas the Hα luminosities are dominated by the hotter stars. The effect of uncounted O stars, WR stars, and B stars suggests that the error bars are actually asymmetric in favor of higher predicted Lyc emission, but these are still likely to be small effects in comparison to that due to O star Lyc uncertainties. Thus we estimate a median value of $L_{\rm obs}/L_{\rm SdK}$ in the range 0.49 – 1.1, or equivalently, a mean fraction of Lyc radiation escaping from these H II regions in the range 0 – 51%. Although formally the lower limit to the range is 0%, we note that the existence of individual nebulae that are quite reliably density-bounded (Table 2) implies that the lower limit is > 0, but is difficult to quantify further.

4 DISCUSSION

While the range of values suggests that a significant escape fraction seems likely, it is also consistent with the nebulae being generally radiation bounded, although Table 2 shows that some individual objects are convincingly density-bounded. But we note that the sample of faint Galactic H II regions studied by Hunter & Massey (1990) also showed an overall excess of available ionizing radiation. That study predicted the Lyc emission rates from observed, classified stellar populations using the P73 conversions, and compared the results with the Lyc emission rates implied by Hα and radio continuum observations. Inspection of their results shows that the median ratio of observed to predicted emission rates is 0.7 for both the Hα and radio-derived comparisons, with 19 objects in the Hα sample and 21 in the radio sample. The results from this Galactic study are thus in good agreement with the median value from our sample of 0.74. Note that the use of the P73 Lyc predictions by Hunter & Massey (1990) imply that the median ratios from their sample are therefore slight overestimates when comparing with our results (cf. Table 2).

An escaping Lyc fraction of up to 51% is fully consistent with the estimated fraction of diffuse to total Hα flux of $35 \pm 5\%$ estimated by Kennicutt et al. (1995) for the LMC. It is therefore indeed quite possible that the WIM, at least in the LMC, is ionized by hot supergiants. If the H II regions in the LMC are typical in their structure, extinction, and relationship to the diffuse ISM, then these results may be compared to observations of the WIM in other galaxies. Measurements for Hα luminosity fractions of the WIM in nearby galaxies range from $\sim 20\%$ to 53% (see Ferguson et al. 1996), which are also consistent with the fraction of ionizing radiation escaping from the LMC H II regions. Thus it is a likely possibility that the WIM in these galaxies is dominated by O star photoionization. With better constraints on the large uncertainties in our estimate of the median $L_{\rm obs}/L_{\rm SdK}$, it should become possible to better evaluate this hypothesis, as well as the role of alternate ionizing mechanisms, which can contribute to the Hα luminosities in both normal H II regions and the WIM as well.

Our selection of H II regions encompasses a range of nebular morphology, including superbubbles, diffuse H II regions, and composite objects. The distributions of $L_{\rm obs}/L_{\rm SdK}$ for these three subsamples are compared in Figure 1. On the whole, the superbubbles may have lower ratios of observed to predicted Hα luminosities; the mean for the 5 superbubbles in this sample is 0.59, as compared to a mean of 0.89 for the 4 diffuse objects. The mean for the 3 composite objects is 0.85. A preferential leakage of ionizing radiation for the superbubbles might be real if actual holes are present in some of the shell walls, as may be suggested by the morphology of some objects. Such holes could allow the escape of ionizing radiation from those superbubbles. Overall, however, Figure 1 shows that the differing morphologies all span a large range in $L_{\rm obs}/L_{\rm SdK}$. In view of possible selection effects and small number statistics, we hesitate at present to attribute any significance to the possible trend with morphology.

Our results are suggestive that many H II regions may be density bounded rather than ionization bounded. As can be seen in Table 2, this may not be the case for any individ-

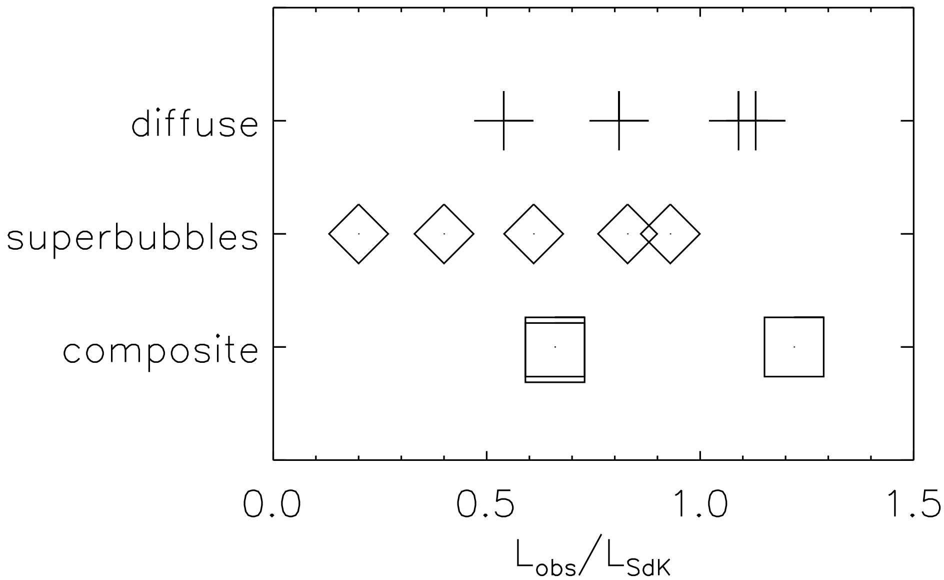

Figure 1. Distribution of $L_{\rm obs}/L_{\rm SdK}$ among the different nebular morphologies. Diffuse H II regions are shown with plus symbols, superbubbles with diamonds, and composite objects with squares. There are two points at $L_{\rm obs}/L_{\rm SdK} = 0.66$ for the composite objects.

ual object, but appears likely for many. Density-bounding of the nebulae will probably have a noticeable effect in the observed emission of lower-ionization species such as [O II], [N II], and [S II], that normally dominate in the outer regions of ionization-bounded nebulae (see, e.g., Shields 1990). Emission-line ratios that are based on species originating in different nebular volumes should therefore be interpreted with some caution, if only ionization-bounded models are considered. Photoionization modeling is necessary to fully investigate this effect, which will be explored in a future study.

The sample spans over one order of magnitude in H II region luminosity, over which there is no obvious correlation between $L_{\rm obs}$ and fraction of escaping Lyc radiation. Rozas, Beckman, & Knapen (1996) have suggested that a change in slope of the H II region luminosity function around $10^{38.6}\,{\rm erg\,s^{-1}}$ is due to the density bounding of objects with greater luminosities, whereas the fainter objects are suggested to be primarily ionization bounded. Most of the nebulae in our sample have luminosities below their critical value, and as seen in Table 2, there is a significant fraction of objects that may be convincingly identified as density-bounded. However, the LMC cannot provide a useful sample of H II regions with $\log L_{\rm obs} > 38.6$, hence it is impractical to further test the hypothesis with this galaxy.

In summary, we find that the H II/OB systems in the LMC suggest that up to 51% of the ionizing radiation from the hot stars is escaping the local H II regions. A significant number of individual H II regions reliably appear to be density-bounded. At present, we find no compelling correlation with nebular morphology or luminosity in the fraction of Lyc photons escaping the H II regions, although superbubbles might possibly exhibit a greater escaping fraction. Our sample of objects should be fairly representative of the variety of H II regions in normal star-forming galaxies, as it includes superbubbles, diffuse nebulae, and complex regions, all with varying luminosities and galactic location. The relative proportion of different nebular types will ultimately depend on the star formation history and environment in any given galaxy. Our estimate of the Lyc escape fraction is consistent with the observed fraction of total Hα luminosity emitted by the WIM in the LMC and other star-forming galaxies, and suggests that photoionization by ordinary O stars could indeed be the dominant source of the ionization for the WIM, although alternate ionization mechanisms are not ruled out.

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